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Final Report for

Airborne Electronic Reset Fuse

Contract No. NAS5-11559

Prepared By:

EMR-Aerospace Sciences
EMR Division
Weston Instruments, Inc.
College Park, Maryland

Prepared For:

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland

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1.0 GENERAL PROJECT REVIEW

1.1 Objective

This report has been prepared in accordance with Article II of contract NAS5-11559.

The purpose of this report is to inform the GSFC Technical Officer of all phases of the project on the Airborne Electronic Reset Fuse.

1.2 Project Summary

The packaged prototype has been completed and is delivered with this report. The following modifications and/or optimizations have been incorporated:

a. The change from a +7V supply voltage to +12V has not been incorporated. To maintain the power dissipation at the present low level, while increasing the supply voltage, is not feasible. The 70 percent increase in supply voltage would require a power dissipation increase of approximately 35 percent. In addition, this would change the stress on several components making it necessary to change their voltage ratings with a consequent increase in size.

b. Both the breadboard and the prototype are capable of demonstrating a fuse of any rating from 1/16 amp to 3 amps. In particular, ratings of 1/16, 1/8, 1/2, and 3 amps have been constructed.

c. Energy storage is provided to allow circuit operation for 1.0^{+} seconds in the event the 7V line were suddenly decreased or shorted.

d. Capability of ground commands to open or close the relay, even in the event of a collector emitter short on Q9, is provided.

e. The time delay versus temperature is significantly improved.

f. The fusing point accuracy versus temperature is stabilized.

g. The time delay variation versus supply voltage changes is reduced.

The modifications/optimizations of the circuit have been incorporated only after careful consideration of their effect on reproducability, manufacturing operations, reliability, power consumption, size, and cost factors.

2.0 TECHNICAL DISCUSSION

2.1 Modifications

The schematic diagram, Figure 2-1, shows the original circuit before the modifications and optimizations. Figure 2-2 is the schematic diagram of the improved circuit. Where possible, the desirable electrical characteristics (i.e., simplicity, low power consumption, reliability) of the original circuit have been presevered, while its capabilities and environmental performance have been enhanced.

2.1.1 Fuse Rating

For the capability of adjusting the fuse to 1/16, 1/8, 1/2, or 3 amp ratings, two basic design approaches were considered:

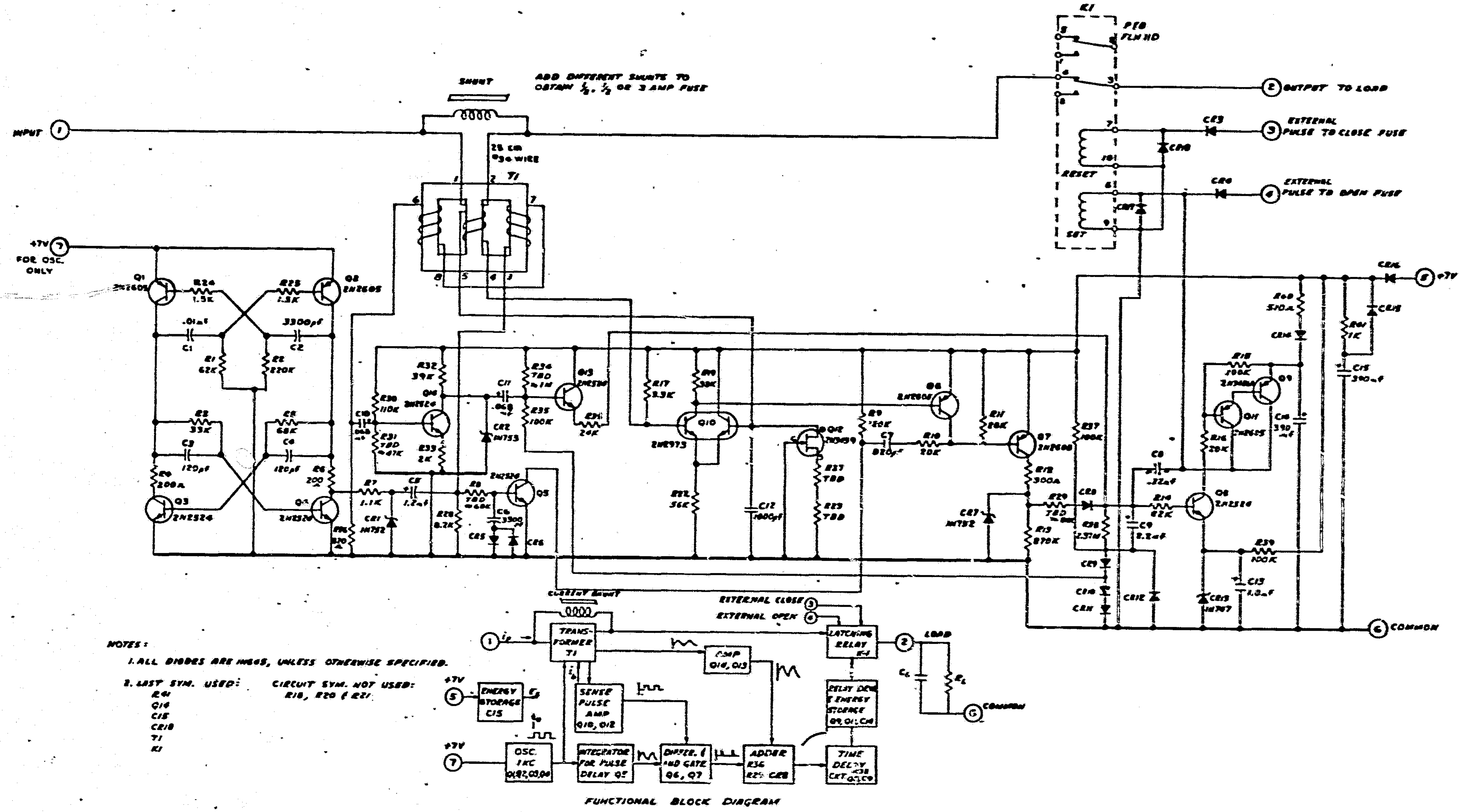
1. Adjust the bias current through the sense winding of the transformer for each fuse rating.
2. Use a basic 1/16 amp fuse circuit configuration, and use precision shunts to shunt the additional fused current around the control winding for higher fuse ratings.

Approach 1 above has several disadvantages:

a. The power drain of the circuit increases with the bias current.

b. The transformer for currents of 1/2 amp and greater would have to be of greater cross sectional area (more iron).

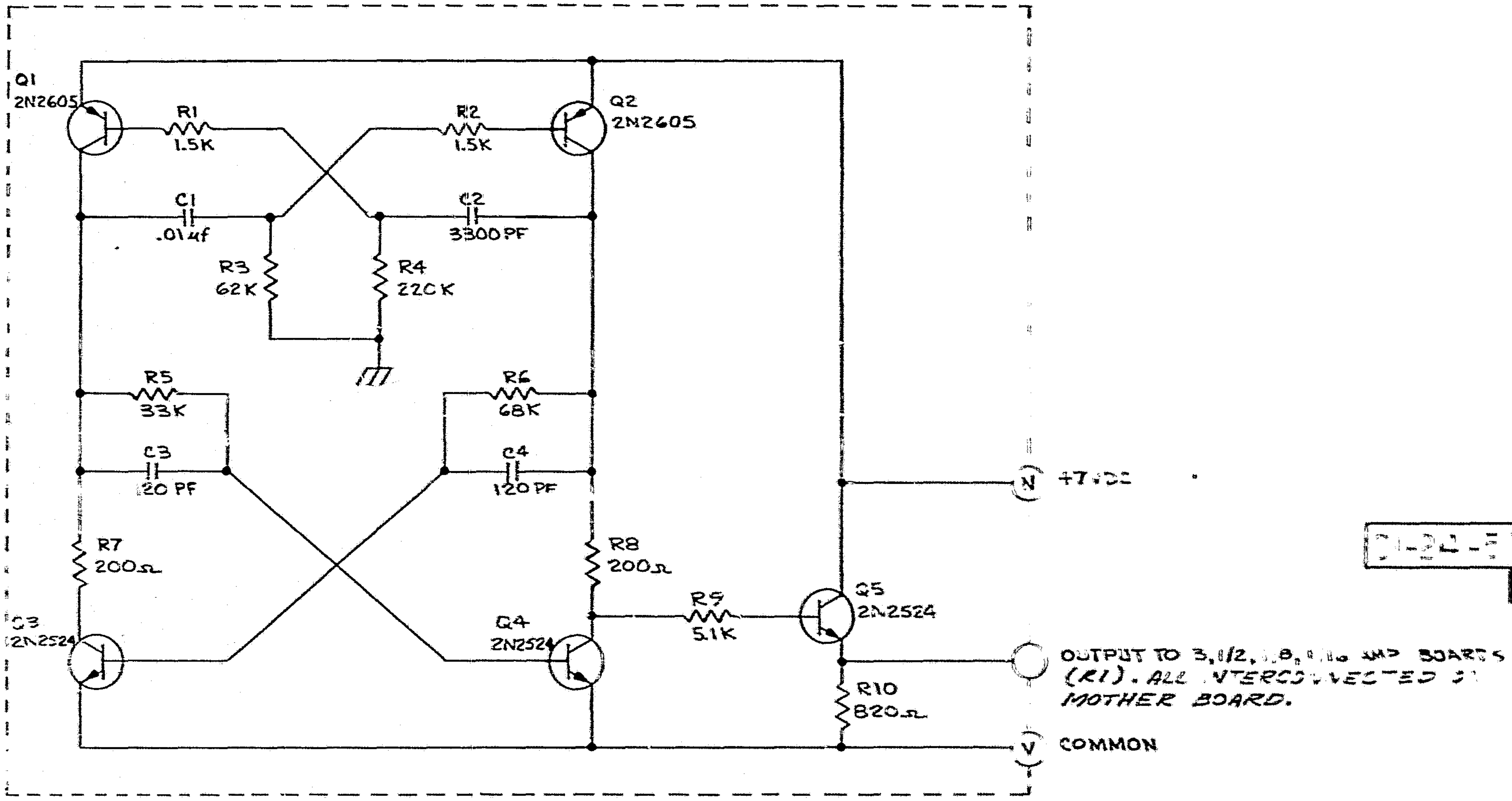
c. The temperature compensation of the JFET would probably have to be changed for each bias current.



INPUT
SHUNT
OUTPUT TO LOAD
EXTERNAL PULSE TO CLOSE FUSE
EXTERNAL PULSE TO OPEN FUSE
RESET
SET
+7V FOR OSC. ONLY
COMMON
NOTES:
EXTERNAL CLOSE
EXTERNAL OPEN
LATCHING RELAY
ENERGY STORAGE C15
SENSE PULSE AMP
ADDER
TIME DELAY
FUNCTIONAL BLOCK DIAGRAM

FIGURE 2-1

REVISIONS			
SYM	DESCRIPTION	DATE	APPROVED



NOTE: UNLESS OTHERWISE SPECIFIED;
ALL RESISTORS ARE 1/4W, ±5%

REQD	PART NO	ITEM	DESCRIPTION	SYM

LIST OF MATERIALS

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ON
FRACTIONS DECIMALS ANGLES

MATERIAL

TREATMENT OR FINISH

DRAWN BY Ostrowski DATE 1-28-70
CHECKED
ENGINEER KS [illegible]
APPROVED
APPROVED

EMR-AEROSPACE SCIENCES DIVISION
ELECTROMECHANICAL RESEARCH, INC
COLLEGE PARK MARYLAND

SCHEMATIC DIAGRAM
1KC OSCILLATOR

CODE IDENT NO	SIZE	
06141	C	01-24-501

SCALE NONE SHEET OF

01-24-500	6341-1956
NEXT ASSY	USED ON

FIGURE 2-2a

Clearprint 1000H-8 Keuffel Co.

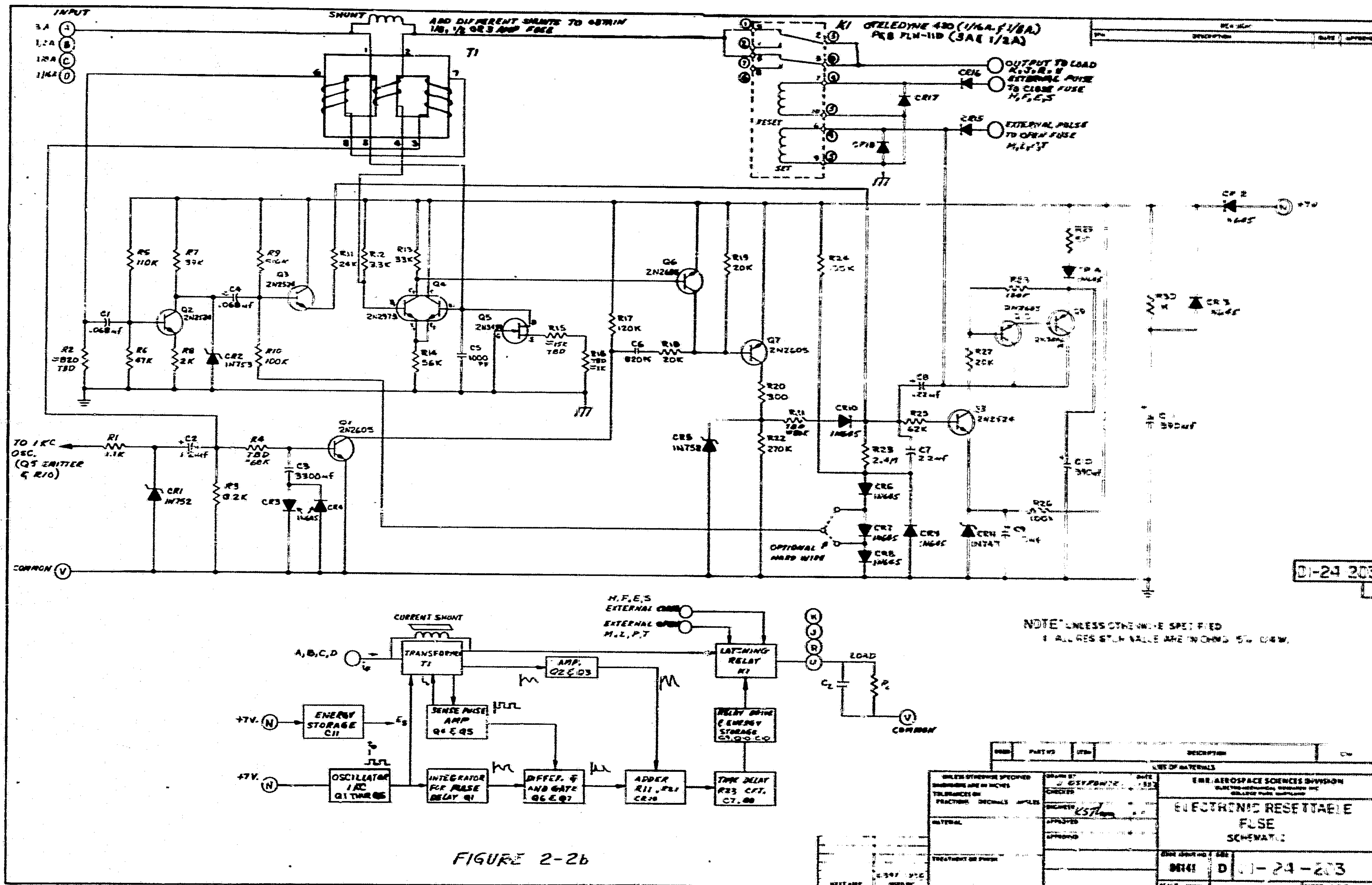

INPUT
SHUNT
ADD DIFFERENT SHUNTS TO OBTAIN 1/8, 1/2 OR 3 AMP FUSE
T1
K1
TELEDYNE 420 (1/16A, 1/8A)
OUTPUT TO LOAD
EXTERNAL PULSE TO CLOSE FUSE H, F, E, S
EXTERNAL PULSE TO OPEN FUSE M, L, P, T
RESET
SET
TO 1KC OSC. (Q5 EMITTER & R10)
COMMON
OPTIONAL HARD WIRE
CURRENT SHUNT
TRANSFORMER T1
AMP. Q2 & Q3
LATCHING RELAY K1
LOAD
ENERGY STORAGE C11
SENSE PULSE AMP Q4 & Q5
RELAY DRIVE & ENERGY STORAGE
OSCILLATOR 1KC Q1 THRU Q5
INTEGRATOR FOR PULSE DELAY Q1
DIFFER. & AND GATE Q6 & Q7
ADDER
TIME DELAY
NOTE: UNLESS OTHERWISE SPECIFIED
1. ALL RESISTOR VALUES ARE IN OHMS 5% 1/4W.
EMR-AEROSPACE SCIENCES DIVISION
ELECTRONIC RESETTABLE FUSE
SCHEMATIC
D
DI-24-203

FIGURE 2-2b

Design approach 2 was selected and allows a basic 1/16 amp circuit configuration to handle currents up to the capability of the latching relay. With this configuration, a shunt, which has been calculated and/or adjusted to give the desired fusing point, is simply inserted in parallel with the control winding. Since the control winding is magnetically coupled to an a.c. circuit (1KHZ) the shunt must present an inductive reactance which is much greater than the leakage reactance of the control winding turns. This makes it necessary to insert a high permeability material in the shunt. Thus, for each fuse rating a shunt wound on a toroid is used to give the desired fusing point. This approach gives great versatility to the fuse since there is simply a basic 1/16 amp fuse circuit, and the rating is changed with different shunts.

The shunts are of magnet wire having a length equal to that of the control winding, but with a cross sectional area proportional to the increase in fusing point desired. Thus, if the control turns wire is 25 cm long and 40 circular mils gives a 1/16 amp fuse, in order to obtain a 1/2 amp fuse requires that the circular mils total be 8 x 40 = 320 cir mils. Subtracting the 40 cir mils already on the control winding, gives 280 circular mils to be added in shunt with a length of 25 cm. When wire selections are such that 280 circular mils is not conveniently obtained, the length of the shunt is adjusted to obtain the proper shunt resistance.

2.1.2 Energy Storage

Two capacitors, C_{11} and C_{10}, have been added to the original circuit. C_{11} provides storage of energy to operate the fuse circuit for approximately one second following a supply voltage failure. C_{10} provides energy storage to operate the relay after the circuit has operated through the time delay. The storage capacitor for the relay is inserted in the circuit so as not to aid capacitor C_{11} in operating the circuit. Thus, C_{10}

remains fully charged until the time delay period has been completed and then delivers its full energy to the relay coil. The values for C_{11} and C_{10} are as follows:

$$C_{11} = \frac{2\ Pc\ tc}{V_0^2 - V_1^2} \qquad\qquad C_{10} = \frac{2\ Pr\ tr}{V_0^2 - V_1^2}$$

where Pc = Power requirement of the circuit (3.4×10^{-3}W)

tc = Time circuit must operate (1.0 seconds)

Pr = Power requirement of relay

tr = Time power must be applied to relay (5×10^{-3} sec.)

V_0 = Voltage capacitor is charged to initially (7.0V)

V_1 = Voltage capacitor is allowed to discharge to in tc or tr (5.5V)

Thus

$$C_{11} = \frac{2(3.4)\ 10^{-3}\ (1.0)}{49 - 30} = 358\ \mu fd$$

$$C_{10} = \frac{2\left(\frac{49}{67}\right)5\times10^{-3}}{19} = 383\ \mu fd$$

In the circuit each capacitor is 390 µfd.

An interesting consideration is: When the 7V drops suddenly or significantly, will the overload current be of such magnitude that the time delay would always be 0.1 second or less. If so, the capacitor C_{11} need only supply energy for 0.1 second (tc). Then C_{11} could be reduced to one-tenth of that calculated above with a considerable saving in the size of the capacitor. Or capacitor C_{10} could supply this energy by adding a diode in parallel with resistor R_{29}, with its cathode at E_s and anode on the Q_9 emitter. The diode (CR_{14}) is then not necessary. This consideration could be made when optimizing the fuse to a particular application.

2.1.3 Command Operation

Provision to ensure the capability of remotely opening or closing the fuse by commands has been incorporated. R_{29} is added to ensure that the fuse may be remotely closed in the event of a failure (collector-emitter short) of Q9.

2.2 Optimizations

It is noted in Figure 2, that diodes have been used in all cases to temperature compensate the circuit. This has several advantages over sensistors or thermistors:

a. The change in forward voltage of a diode with temperature will approximately track the Vbe of the transistor which is causing the temperature dependence.

b. Thick film or thin film is more feasible with diodes than sensistors/thermistors.

c. Diodes are less expensive and more reliable.

2.2.1 Time Delay Versus Temperature and Overload Current

The delay time required to open the fuse as a function of temperature and overload current has been improved and a curve of typical circuit characteristics is shown on Figure 3. The circuit configuration is such that this characteristic may be conveniently modified to change: the curves' slope, its minimum time delay, and the overload at which the time delay begins to decrease. Compensation of this time delay with temperature is dependent on several components:

a. Vbe of Q_8 - (nominally $\frac{2mV}{^oC}$)

b. Temperature coefficient of C7 - (nominally $\frac{400 \text{ parts}}{\text{million } ^oC}$)

c. Vbe of Q_7 - ($\frac{2mV}{^oC}$)

d. Frequency change in the oscillator

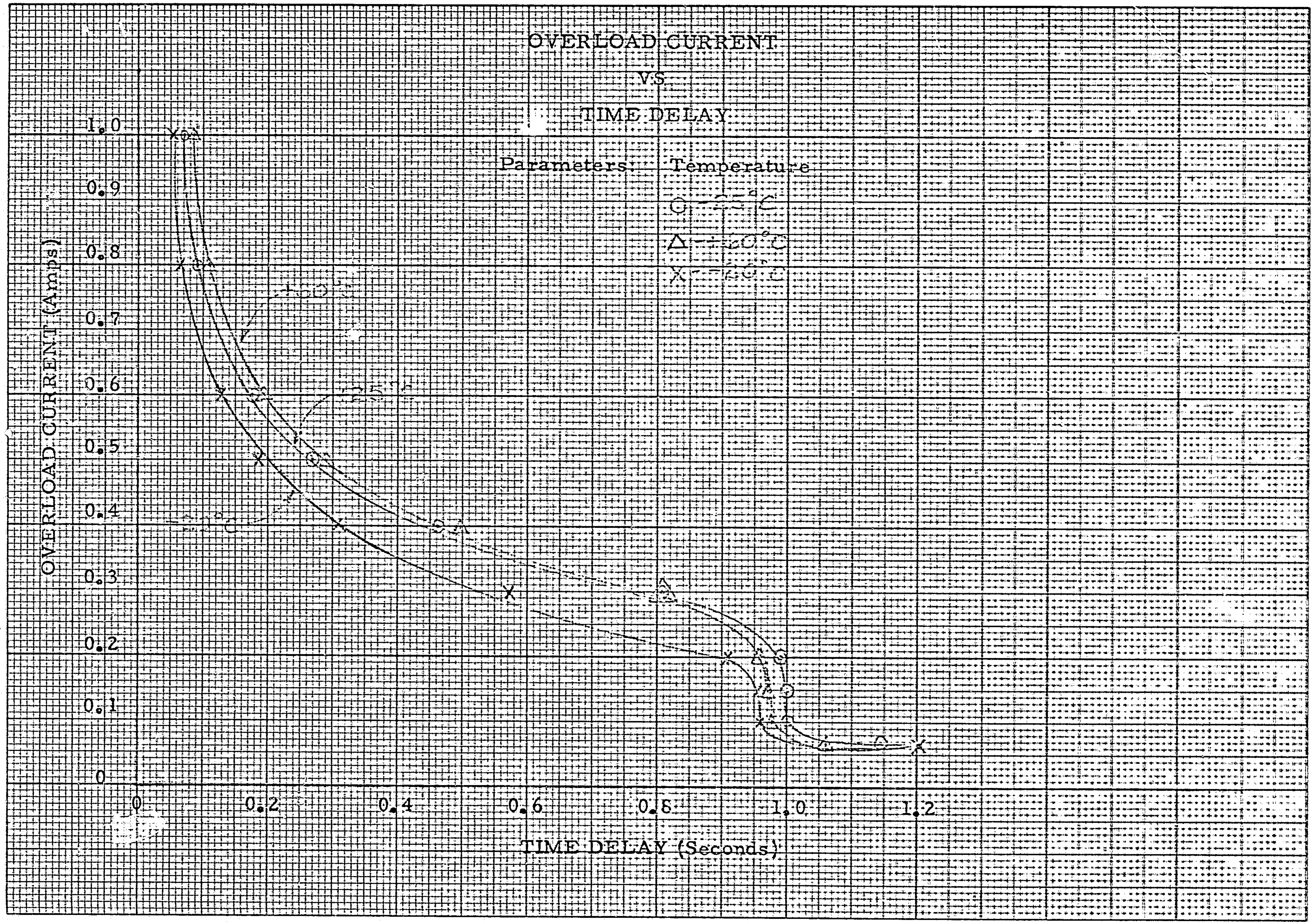
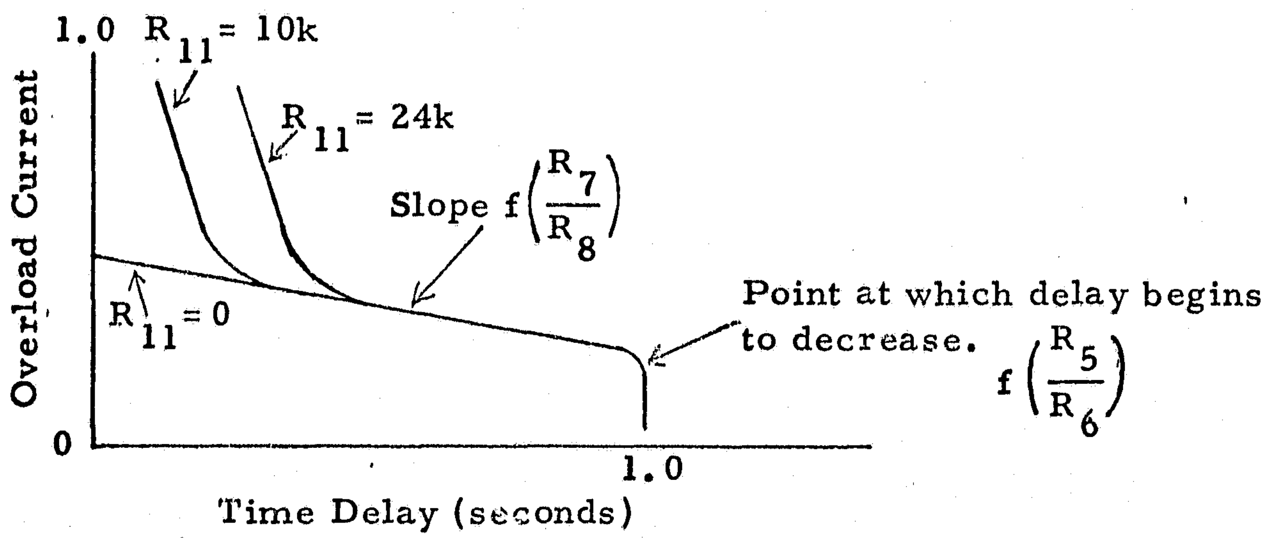

OVERLOAD CURRENT
VS
TIME DELAY
Parameters: Temperature
OVERLOAD CURRENT (Amps)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1.0
1.2
TIME DELAY (Seconds)

FIGURE 2-3

Compensation of these variables is obtained using diodes CR_6, CR_7, and CR_8. In some situations, only two of the three diodes may be necessary. This is dependent on the amount of compensation required. To provide the inverse time delay with overload current, it is necessary to amplify and provide control of the d. c. level of the signal fed back from R_2. This added amplifier provides convenient control over the i_f versus t_d characteristic.

Transient Response

The circuit has a feature incorporated to allow high current transients through the fuse without opening. This provision is a function of resistor R_{11}, which establishes the minimum time delay at high overload currents. The sketch below shows the effect of R_{11}. This is considered a very valuable feature in that it may be easily adjusted to meet the need of a particular experimenters' transient requirements.



Accuracy

Since the transformer is the component which detects the current overload, the fusing point accuracy is affected by the transformer hysteresis. The bias current flowing in the sense winding magnetizes the transformer center core. A residual magnetism will remain in this core, even with the bias current removed due to the coercive force of the magnetic material. Current overloads applied for a sufficient period of time will negate some of the magnetization due to the bias current and thus lower the point (overload current) at which the fuse will open. Laboratory tests of this effect show that with the time delays of 1.0 seconds or less, the effect is approximately 5 percent.

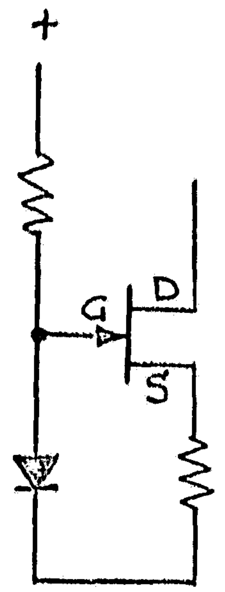
2.2.2 Time Delay Stability Versus Supply Voltage Changes

To compensate the circuit against changes in supply voltage, several voltage reference diodes were added. The choice here was to either regulate the input voltage which would increase the power drain or regulate the individual circuit signals. The latter technique was employed.

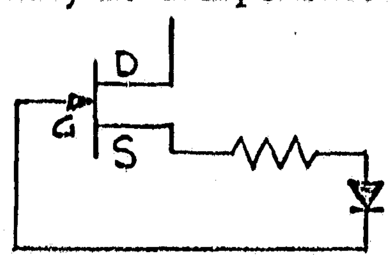
2.2.3 Fusing Point Accuracy Versus Temperature

The fusing point is affected by changes in the bias current through the sense winding of the transformers. The JFET (2N3459) Q_5 is a constant current source and must either be biased where its temperature coefficient is zero or be temperature compensated. JFET's exhibit a temperature characteristic where for high currents (i_d) the temperature coefficient is negative and for low currents it is positive.

In the circuit application, the bias current (i_b) is low ($\approx 20\mu A$) and the FET temperature coefficient is positive. Without compensation, the fusing point will increase with increasing temperature, if other effects may be neglected. To compensate for this effect, diode compensation may be added as shown below:



If the net effect of other variables is to decrease the fusing point with temperature, the FET may be compensated as shown below:



An interesting and perhaps valuable consequence of this compensation is that almost any fusing point characteristic versus temperature may be obtained. Since many of the equipments to be fused in a spacecraft draw increasing current with increasing temperature, a positive slope to the fuse characteristic may be desirable and can be easily obtained.

Conversely, if a negative slope is desired, it may easily be obtained. If a single diode greatly over compensates the FET, then sensistors/ thermistors must be used. The amount of compensation required is a function of the individual FET. The variation of temperature coefficients between FET's within the family of 2N3459's has not yet been established. The particular FET in the circuit does not need compensation; however, a sufficient sample to establish its relationship to the family has not been evaluated.

2.3 Circuit Operation

Basically, the electronic fuse consists of two parts, the switch which breaks the power line and the current sensor. A latching relay was specified as the power line breaking element because of its inherent advantages of negligible power dissipation, and capability of storing its state of operation, thus eliminating a binary circuit.

The method of sensing load current forms a starting point for design. Consider the magnetic configuration shown in Figure 2-4. A balanced oscillator winding is placed on the two outside legs (Windings A and B) and a sense winding (Winding C) and a control winding (Winding D) are placed on the center leg of the magnet. Because the oscillator windings are balanced and in phase, the AC flux developed by these windings cancel in the center leg. The purpose of the AC excitation is to produce an AC flux which saturates the outside path at waveform peak points.

Now consider that a DC current is passed through the control winding (Winding D). This current produces a DC flux in the center leg which completes its loop through the two outside paths. The outside path, however, is placed in and out of saturation due to the AC excitation discussed above. The DC flux path is therefore completed only during the intervals when the outside path is in the unsaturated condition because the path acts essentially as an open circuit to the DC flux when it is in the saturated condition. It is also noted that the outside loop is placed into and out of saturation twice per excitation cycle. Because of this phenomena, an AC voltage appears across the sense winding (Winding C) which is twice the frequency of the excitation waveform whenever a DC current is passed through the control winding (Winding D).

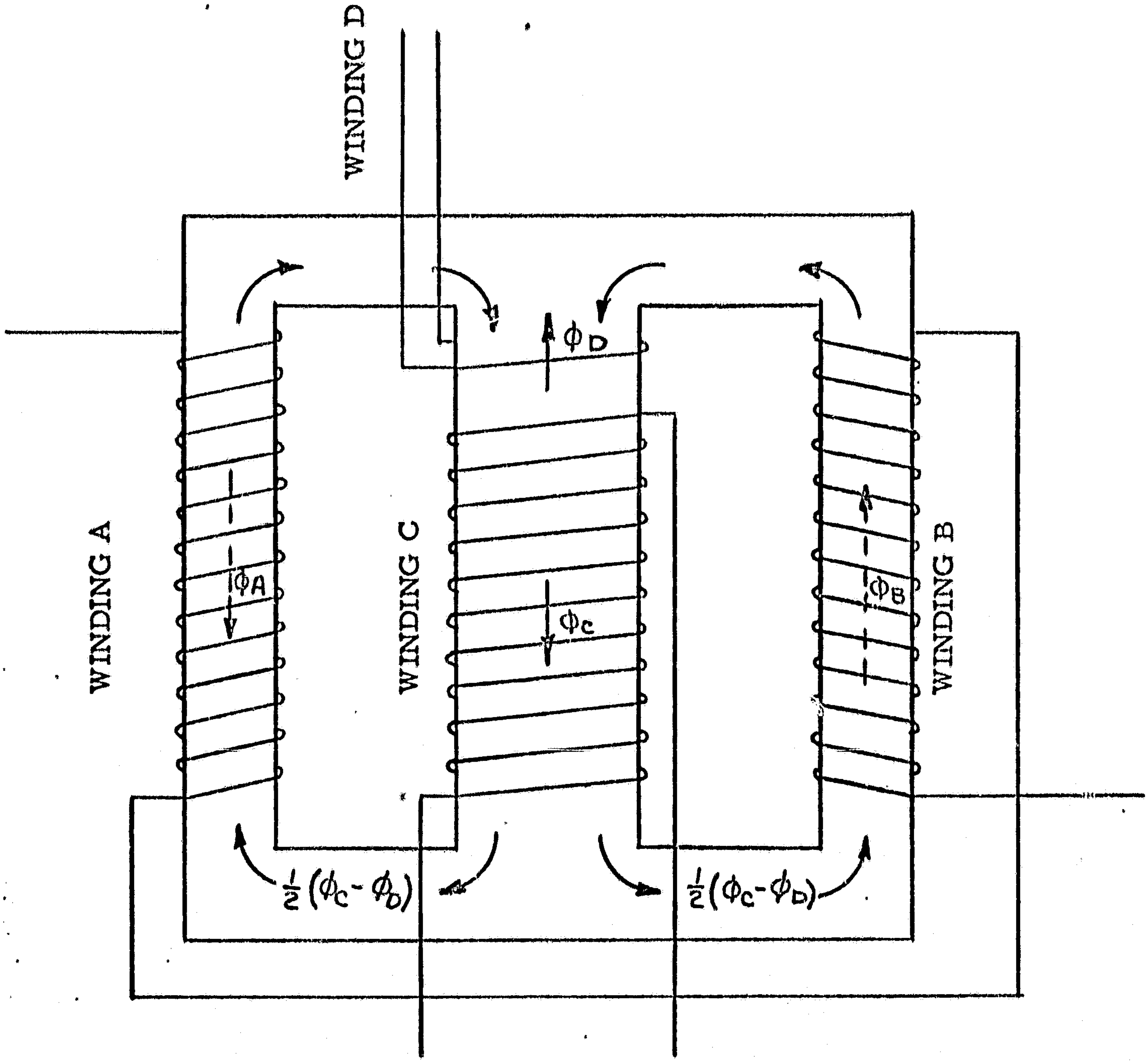


FIGURE 2-4 TRANSFORMER

The control winding has only one turn and the sense winding has approximately 1000 turns around the center leg of the transformer. In the actual case, a DC bias current is passed through the sense winding in such a direction as to cause the induced flux to be opposite to the induced flux produced by positive current through the control winding. Under this condition as the current through the control winding gradually increases, there will be a point where the flux induced by the control winding exceeds the DC flux induced by the sense winding. At this point, the phase of the AC voltage induced in the sense winding changes 180°. The phase reversal characteristic is the phenomena utilized in the fuse detection circuitry. The fusing point is determined by the following relationship:

$$I_f = N_s I_s$$

where:

I_f = Fusing Current

N_s = Number of sense winding turns

I_s = Sense winding DC bias current

It should be noted that the fusing point can easily be made any value by controlling N_s for course adjustment and I_s for precise adjustment.

Permalloy 80 was selected as the transform core material due to its low magnetizing force. The core consists of 30 layers of .004 gage EE laminations. The laminations are Magnetics Inc., part number EE-28-29-4D.

The circuit shown in Figures 2-2a and 2-2b is composed of five parts: The transformer, oscillator, phas detector, relay driver, and latching relay. The AC excitation current for the transformer discussed earlier is produced by the oscillator, Q1 through Q5 of Figure 2a. The oscillator is a complementary circuit which was selected because of its low power dissipation and low output impedance. The output is capacitively coupled to both the oscillator windings of the transformer and to the phase detector.

The phase detector (Q4) detects the phase reversal point of the transformer sense winding induced signal. When the current flow through the control winding is below the fusing level, the sense winding senses a signal of one phase. When the current exceeds the predetermined level, the sense winding senses a 180 degree phase shift of the induced signal (a square wave). This signal is amplified by differential amplifier Q4 of Figure 2b and applied to transistor Q6 which turns off, allowing negative pulses (derived from the oscillator square wave through Q1) appearing at the C6-R18 junction to turn on Q7 and apply positive pulses to the relay drive circuit through a delay network (R23, C7, Q8). If the signal lasts long enough, sufficient pulses will build up until the threshold of Q8 is reached turning on Q10 and Q9 which sets the relay, opening the main current path. In the event of a significant overload, transistors Q2 and Q3 provide a DC output to C7 which is proportional to the magnitude of the overload, charging it more rapidly than the pulses from Q7 alone. In this way the time period from initial overload to opening of the relay is made an inverse function of the magnitude of the overload. Once the latching relay is set, an external pulse is required to the reset winding of the relay to close the main current path. Provision is also made to allow an external pulse to be used to set the latching relay and thus open the main current path. Two capacitors are included in the circuitry to provide energy storage for operation of the fuse circuit in the event of a loss of the +7 volt supply. C11 stores sufficient energy to operate the sensing circuits for approximately one second after +7 volt loss. C10 provides sufficient energy to operate the set winding of the latching relay.

3.0 PACKAGING

3.1 Physical Size of Fuse

The physical size of a fuse is dependent on the desired current rating. The largest of the components for a fuse are:

a. The relay
b. The storage capacitors
c. The transformer
d. Transformer shunts

The relay used on the breadboard (P&B FLH 11D) has a 5A rating and is physically large. To conserve space in the prototype, a TO-5 size relay was selected for the 1/16 and 1/8 amp fuses and a crystal can relay was selected for the 1/2 and 3 amp fuses.

The two storage capacitors are large, but necessarily so if this feature is to be retained.

The transformer size is as small as feasible. Also, the size of the toroids for the shunts are essential, unless the transformer is made larger. Thus, the size of the transformer-toroid combination has been reduced as much as practical.

3.2 Prototype Package

Both thin film and thick film packaging of the prototype fuse were investigated. Several vendors were contacted in an attempt to obtain a practical proposal for packaging. In all cases, it was determined that it was impossible to incorporate the large storage capacitors, the TBD resistors, and the relay as part of the film package. Therefore, it was impractical to go to the thin or thick film process since the space saving was extremely small while the expense became very great.

The alternative to thick or thin film packaging is to use a cord-wood construction technique. Several packaging approaches utilizing cord-wood techniques were considered and the final choice was to package the oscillator and each of the fuse elements as separate modules. A motherboard was designed upon which the modules can be placed so that all electrical connections can be made to one connector. The motherboard design for the prototype was arranged to have one oscillator and one each of the four fuse element sizes: 1/16, 1/8, 1/2, and 3 amps. Because of the flexibility of modular construction of each of the elements, it is very easy to design a motherboard having an oscillator and the required fuse elements which is tailored to a specific application. This removes any requirement for redesign of elements for each application.

4.0 PERFORMANCE SUMMARY

4.1

The prototype unit which has been discussed in previous sections has been tested over a temperature range of -20°C to +60°C. The following pages provide tables of test results and graphical plots of the more significant parameters. Data is provided as follows:

VARIATION IN TRIP POINT WITH TEMPERATURE

	-20°C		+25°C		+60°C	
	TRIP POINT	VARIATION	TRIP POINT	VARIATION	TRIP POINT	VARIATION
1/16 AMP FUSE	76 ma	+10.0%	65 ma	-5.8%	62 ma	-10.0%
1/8 AMP FUSE	130 ma	+1.2%	127 ma	-1.2%	127 ma	-1.2%
1/2 AMP FUSE	620 ma	+7.0%	550 ma	-5.2%	540 ma	-7.0%
3 AMP FUSE	2.95 amp	+2.6%	2.8 amp	-2.6%	2.9 amp	+0.9%

Table 4-1

VARIATION IN TIME DELAY WITH TEMPERATURE

	overload current	-20°C time delay seconds	+25°C time delay seconds	+60°C time delay seconds
1/16 AMP FUSE	70 ma	1.22	1.28	1.22
	120	1.01	.95	.93
	180	.81	.86	.80
	240	.43	.48	.48
	300	.23	.26	.24
	360	.14	.15	.16
1/8 AMP FUSE	140 ma	.89	.88	.92
	250	.90	.91	.95
	375	.78	.84	.88
	500	.44	.56	.54
	625	.22	.28	.26
	750	.17	.16	.17
1/2 AMP FUSE	0.7 A	.95	1.02	.83
	1.0	.84	.80	.81
	1.5	.72	.74	.69
	2.0	.52	.51	.53
	2.5	.30	.31	.28
	3.0	.22	.22	.20
3 AMP FUSE	3.5 A	.97	.88	.92
	6.0	.88	.86	.87
	9.0	.86	.85	.82
	12.0	.81	.75	.77

Table 4-2

VARIATION IN TRIP POINT

WITH POWER SUPPLY VOLTAGE AND TEMPERATURE

	power supply voltage	-20°C Trip Point	+25°C Trip Point	+60°C Trip Point
1/16 AMP FUSE	+10%	77 ma	65 ma	62 ma
	nominal	76	65	62
	-10%	80	66	64
1/8 AMP FUSE	+10%	132 ma	130 ma	127 ma
	nominal	130	127	127
	-10%	125	130	125
1/2 AMP FUSE	+10%	.61 A	.55 A	.54 A
	nominal	.62	.55	.54
	-10%	.64	.56	.55
3 AMP FUSE	+10%	3.10 A	2.90 A	2.90 A
	nominal	2.95	2.80	2.90
	-10%	2.90	2.75	2.85

Table 4-3

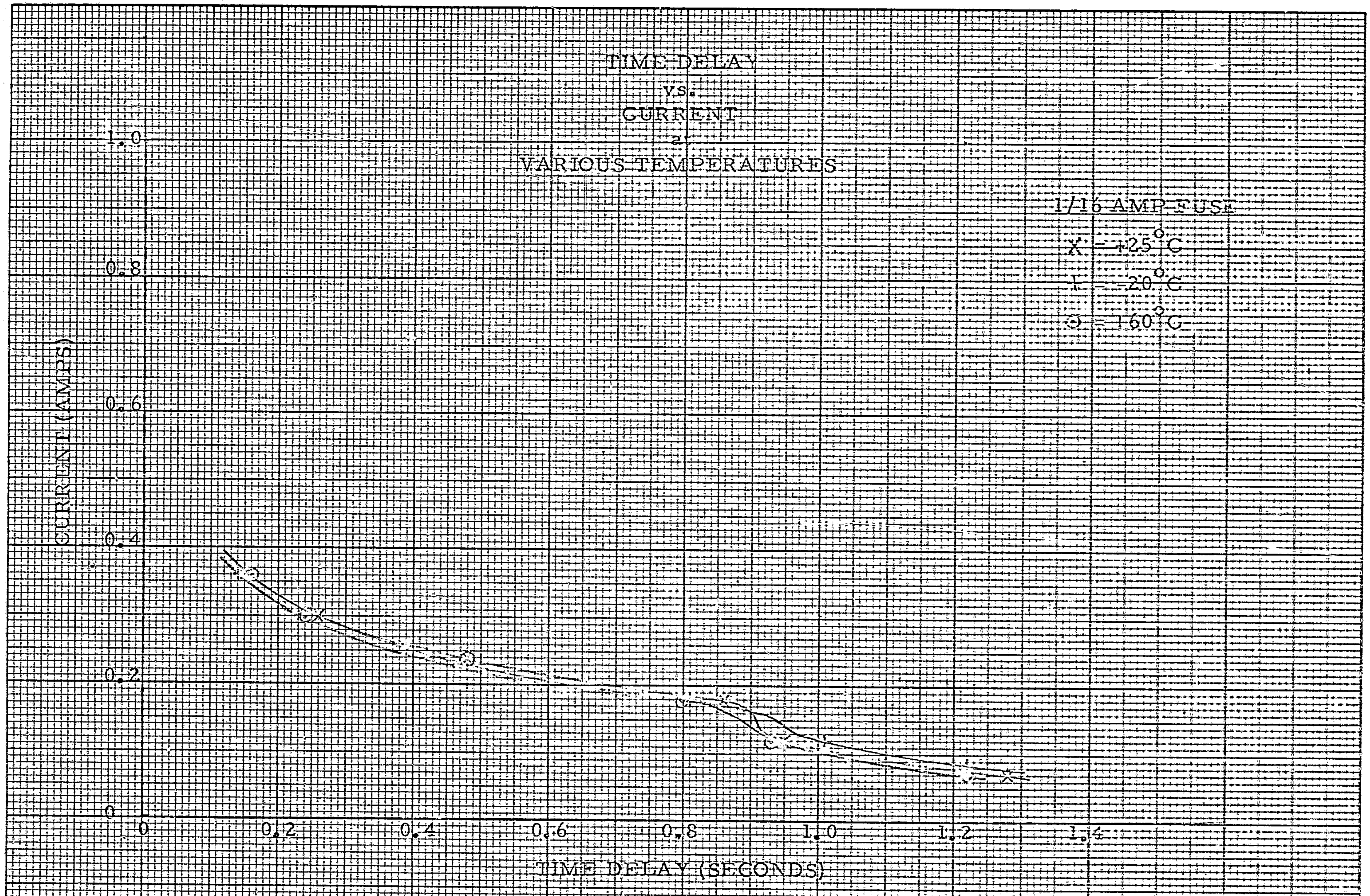


Figure 4-1 1/16 AMP FUSE

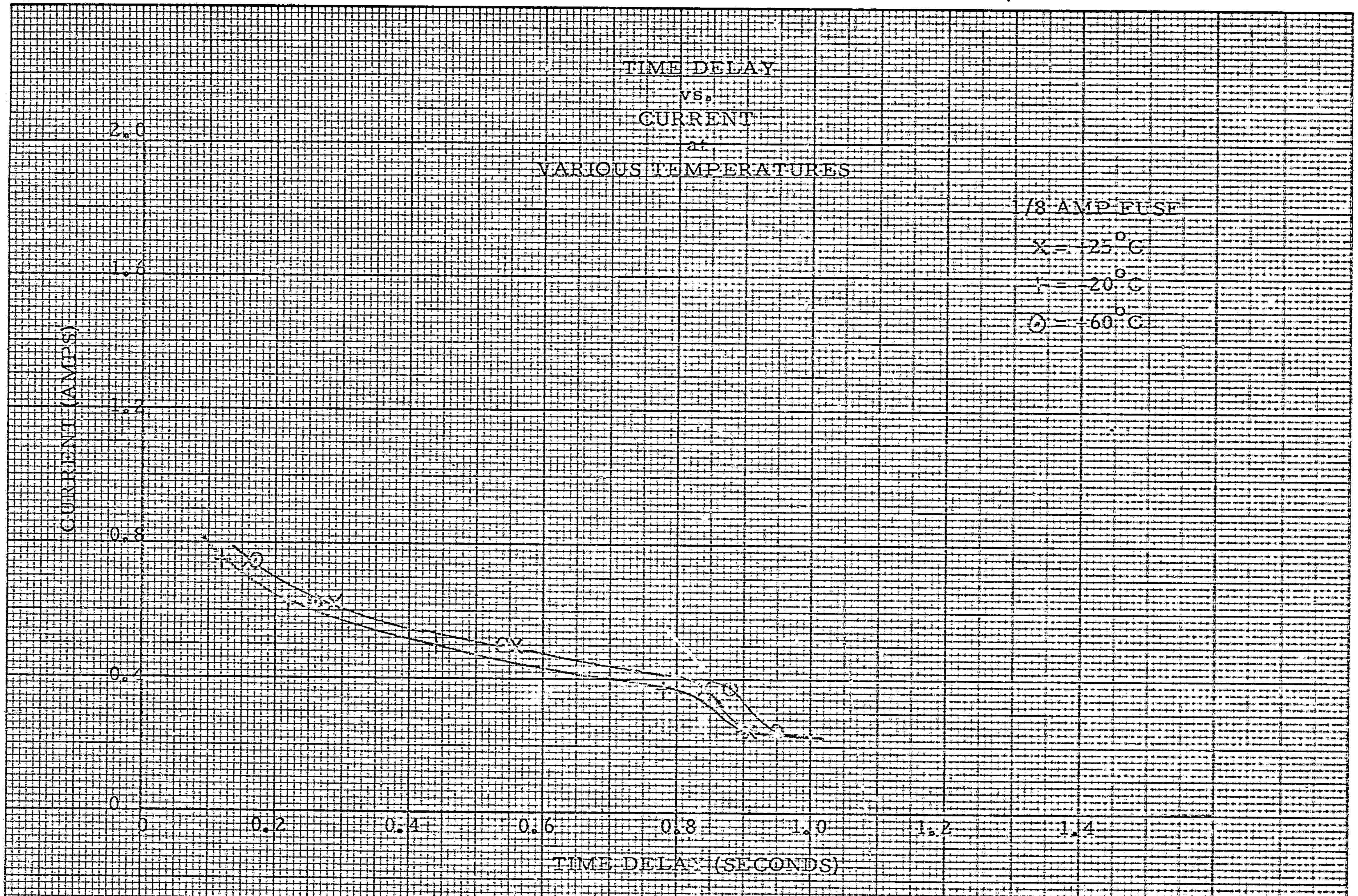


Figure 4-2 1/8 AMP FUSE

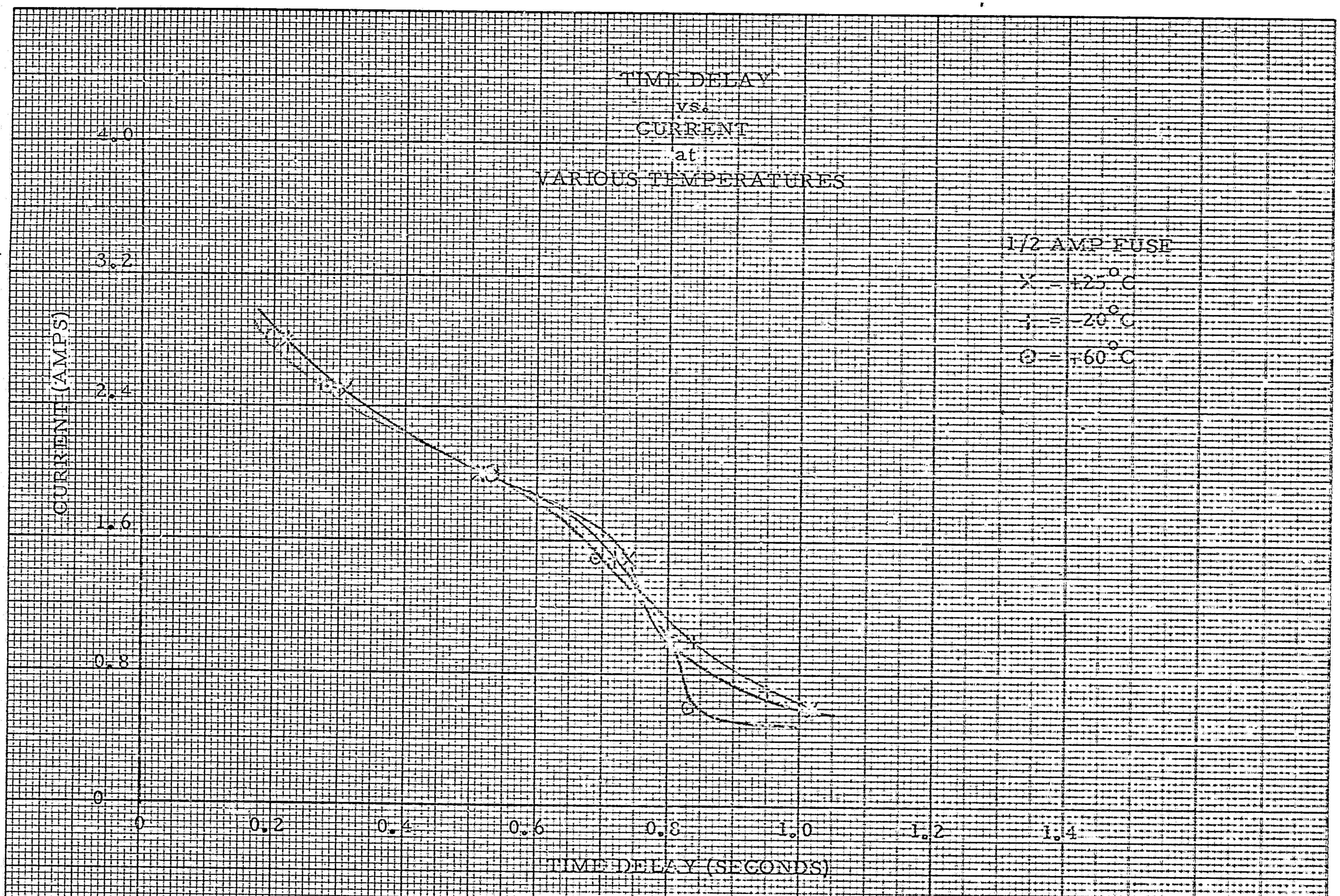


Figure 4-3 1/2 AMP FUSE

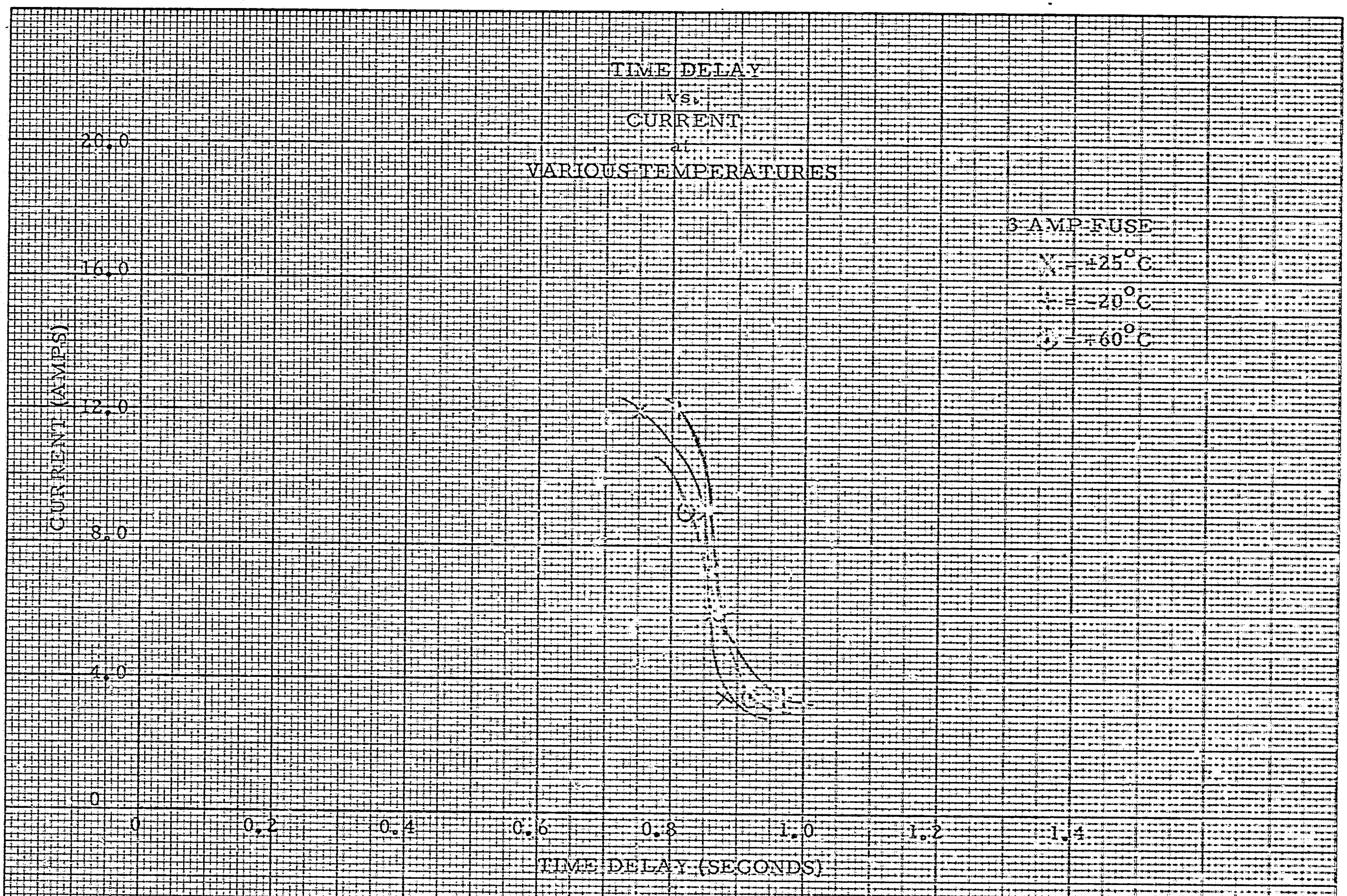


Figure 4-4 3 AMP FUSE

5.0 CONCLUSIONS AND RECOMMENDATIONS

The circuitry designed during the present contract results in a highly versatile device which is applicable to almost any fusing problem. Operation is independent of the polarity and voltage level of the fused line, the current to be fused, the temperature range of operation and most other parameters which are normally considered in spacecraft design. However, to incorporate this high degree of versatility, results in a relatively large package. In the majority of applications, several of the variables can be defined prior to final design and thus safety features which are required in a generalized design can be modified or removed for a specific application. This is true with the present design, also. Therefore, it would be advisable to review mission requirements when applying the fuse so that weight and space savings can be made. Since this will involve reducing versatility and complexity, the modifications are straightforward.

During the time that development of the present fuse circuitry was being done, the state-of-the-art in electronic components has been advancing. There are now available precision operational amplifiers which exhibit excellent temperature stability yet are quite inexpensive. There is a possibility that a new design utilizing operational amplifier techniques and incorporating some of the circuitry of the present fuse would result in a circuit having similar performance and capability but requiring less .BD components, occupying a small volume and having a lower total material cost. If resetable fuses become more standard in spacecraft applications, this approach should be pursued.